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Interacting Stellar Wind and Photoionization Models of the SN 1987A remnant

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Abstract. We are investigating the SN 1987A remnant by modeling the circumstellar environment of the progenitor star. Interacting stellar winds models have been reasonably successful at reproducing the gross features of the nebula, but some details, such as the early rise of the radio and x-ray emission from the supernova blast and the presence of the outer rings, are not explained in a pure wind model. In this paper we describe preliminary results from 2-D models that incorporate the effects of photoionization due to radiation from the central star. These models have successfully produced a thick HII region, as needed to produce the early radio and X-ray emission. The HII region is thickest away from the equatorial plane. The models have also produced a feature resembling the outer rings, but we suspect this to be an artifact of the 2-D calculations that would not persist in 3-D.

1. Introduction

Observations of the SN 1987A nebula give us the clues that we will need to model its structure. Figure 1 shows an HST image of the nebula (Burrows et al. 1995) and a schematic diagram of the nebular structure. The HST image shows two of the salient features of the nebula: the inner and outer rings. The diagram shows a slice containing the symmetry axis. The inner ring lies in the equatorial plane at a radius of about 0.6 lt yr and is expanding with a velocity of 10.3 km s^{-1} (Crotts & Heathcote 1991), while the outer rings are at an angle of about 55° from the equatorial plane and an axial radius of about 1.4 lt yr. A tenuous shell connects the inner and outer rings (Crotts, Kunkel, & Heathcote. 1995), but the shell does not extend past the outer rings; that is, the nebula is open along the symmetry axis.

In an interacting winds model for the nebula, a fast, hot wind ejected during a blue supergiant phase overtakes a slow, dense wind ejected from a previous red supergiant phase. In order to produce the equatorial ring the RSG wind must be asymmetrical, with higher density at the equator and lower density at the symmetry axis. Blondin & Lundqvist (1993) performed numerical simulations of this interacting winds scenario for adiabatic and radiatively cooling gas. These simulations showed that the interacting winds model could produce the inner ring and the overall shape of the nebula. However, the Blondin and Lundqvist models did not produce the outer rings, and the shell in these models is complete

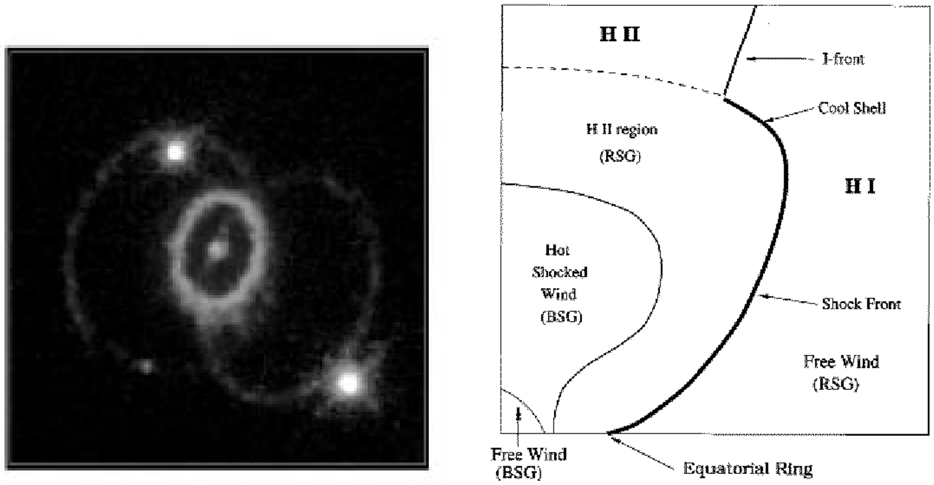

Figure 1. Left: HST image of the SN1987A nebula (Burrows et al. 1995). Right: schematic diagram of the structure of the nebula (Chevalier & Dwarkadas 1995). The schematic shows a two-dimensional section containing the symmetry axis.

all the way to the symmetry axis. Therefore, the interacting wind models need some refinement if they are to describe the SN 1987A nebula.

Radio and x-ray observations of the nebula since 1990 provide additional information. These observations indicate that the supernova blast has encountered a region of density intermediate to the inner and outer winds (Gorenstein, Hughes, & Tucker 1994; Beuermann, Brandt, & Pietsch 1994; Staveley-Smith et al. 1993; Gaensler et al. 1997). The slow expansion of the radio source indicates that this material is too dense to be shocked BSG wind. Chevalier & Dwarkadas (1995) proposed that the intermediate density material is RSG wind that was photoionized by radiation from the progenitor, a B3 Ia star.

In this paper we explore the interacting winds scenario, including photoionization from the progenitor star, as a model for the SN 1987A nebula. Section 2. discusses the features of our numerical fluid dynamics code. Section 3. gives some preliminary results from our numerical simulations, and section 4. compares the results to SN 1987A observations and discusses our plans for future refinements to the models.

2. Numerical methods

For our calculations we use a two-dimensional Eulerian finite difference code with a van Leer monotonic transport algorithm. We use an ideal gas equation of state, $p = (\gamma - 1)\epsilon$, where ϵ is the internal energy density, and the adiabatic constant, $\gamma = 5/3$. The coordinate system is spherical-polar with reflecting boundary conditions at the equator and pole. The inner boundary condition is an inflow condition, set to match the characteristics of the BSG wind, and similarly the outer boundary condition is an outflow condition set to the characteristics of the RSG wind.

In addition to the standard fluid dynamics equations, the code has several features that are necessary for this particular problem. These features include grid expansion, ionization and recombination, radiative cooling, and separate advection for neutral and ionized gas. They are described fully in Rosenberg, Link, & Chevalier (2000).

The RSG wind is characterized by its the mass loss rate, velocity, and temperature, $\dot{M}_R$, v_R, and T_R. Since the RSG wind is asymmetric, $\dot{M}_R$ is actually the mass loss rate that would be experienced if the rate were everywhere equal to its value at the equatorial plane. The angular dependence of the mass loss rate is described by

$$\dot{M}_R(\theta) = \dot{M}_R\left(\frac{\pi}{2}\right)\left[1 - A\frac{\exp(-2\beta\cos^2(\theta)) - 1}{\exp(-2\beta) - 1}\right], \tag{1}$$

where $A = 1 - 1/R$, R is the ratio of equatorial to polar density in the wind, and β controls the steepness of the falloff from the equatorial value. Larger values of β produce distributions more strongly peaked at the equator; while smaller values produce a more gradual falloff. The BSG wind is similarly described by its mass loss rate, velocity, and temperature, $\dot{M}_B$, v_B, and T_B. Finally, the ionizing flux is described by the total flux of photons above the ionization threshold, S_*. The temperatures T_A and T_B are sufficiently low that they do not affect the results. Compared to the computations of Blondin & Lundqvist (1993), S_* is the only additional parameter.

Table 1 gives the parameters for the models used in our calculations. Model 'A' is a fiducial model that was chosen for comparison with previous results (*e.g.* Blondin & Lundqvist 1993).

Table 1. Model Parameters

Identifier	$\dot{M}_R$ ($10^{-5} M_\odot$/yr) $\dot{M}_B$ ($10^{-8} M_\odot$/yr)	v_R (km/s) v_B (km/s)	R	β	S_* (10^{45} s^{-1})
A	7.5	5.0	20	4	4.0
	7.5	450			
XA	7.5	5.0	20	4	0.0
	7.5	450			
B	7.5	5.0	20	8	4.0
	30	450			
C	4.0	5.0	20	8	4.0
	7.5	450			

3. Results

Figure 2 shows a greyscale image of the final state of the fiducial calculation. The criterion for stopping the calculation is that the radius of the inner ring

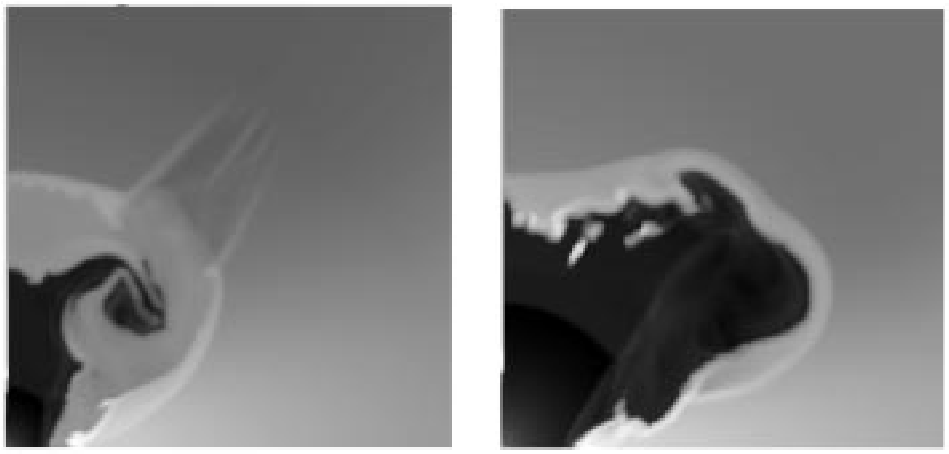

Figure 2. The final states of models 'A' (left) and 'XA' (right). Higher density is represented by lighter colors. The two models are identical, except that model 'XA' has no photoionizing flux. The medium gray region just inside the neutral shell in model 'A' is composed of photoionized RSG wind.

in the calculation reaches 6×10^{17} cm, which is approximately the measured radius of the inner ring in the nebula. The figure shows clearly the inner ring and HII region. However, there is no clear outer ring. Moreover, although the ionization front has broken out at the middle latitudes, the neutral shell is still intact near the pole, in contrast to observations. Further evolution of the model would result in photoionization of the polar shell.

Model 'XA' (fig. 2) has identical parameters to model 'A', except that the photoionizing flux has been turned off. Since there is no photoionizing flux, there is no HII region. The properties of the inner ring, including the expansion velocity, are mostly unchanged from the photoionization case; however, the structure in the middle latitudes is quite different. Particularly striking is the fragmentation in the neutral shell, which leads to dense clumps that look like they might form outer rings; however, these clumps appear to be formed by a Rayleigh-Taylor or similar instability, and therefore they should not be expected to exhibit the azimuthal symmetry required to form the outer rings.

The left panel of figure 3 shows the final state of Model 'B'. Model 'B' has a stronger BSG wind than the fiducial model, and it also has a more strongly peaked (higher β) RSG wind. We see in figure 3 the beginning of a high-latitude ionization front breakout that could eventually destroy the neutral shell near the pole. There is also a neutral clump that might form an outer ring; however, a mid-latitude ionization front breakout has disconnected the clump from the rest of the neutral shell. The HII region is thick throughout most of the model; however, right at the equatorial plane it becomes very thin. Apparently the ionized gas is advected away from the equator, possibly due to the strong peak in the density of the RSG wind.

Finally, Model 'C' is shown in the right panel of figure 3. The density of the RSG wind is lower than in the other simulations we have discussed; consequently,

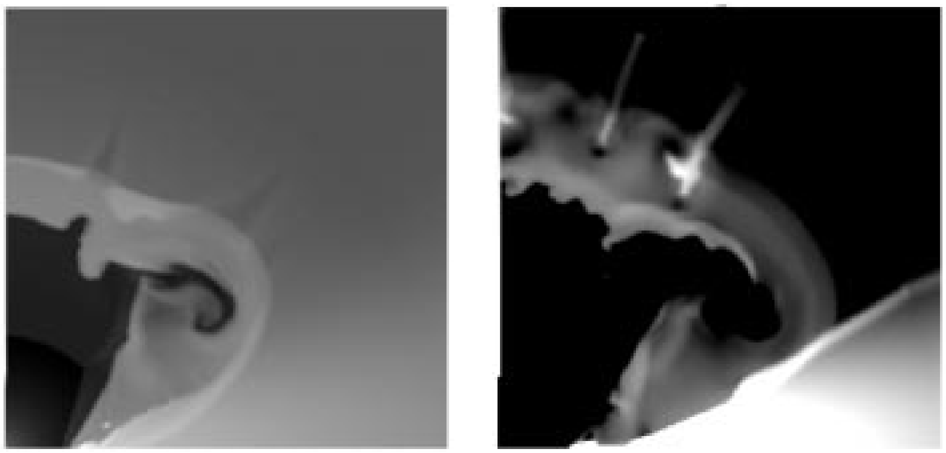

Figure 3. The final state of models 'B' (left) and 'C' (right). Model 'C' forms a 'ring' by ionizing most of the outer shell, leaving a blob of neutral gas.

most of the RSG wind above about 30° is ionized. A dense blob of neutral gas remains at mid-high latitude. This neutral gas appears to survive longer than the rest of the shell because it is compressed by converging shocks preceding the ionization fronts. It is possible (although not certain) that such a blob could form a ring in three dimensions; however, it does not seem possible to form both a ring and a connecting shell through this mechanism. Moreover, the 'ring' is short-lived. The photoionizing flux must last long enough to blow away the surrounding shell and then turn off before it blows away the ring as well. Such a coincidence seems unlikely.

Table 2. Summary of results

id	$r_{\rm ring}/r_{\rm HII}$	Outer Ring?	$v_{\rm shell}$
A	1.20	no	7.2
B	1.10	yes	7.6
C	1.05	yes	9.6
D	1.21	no	7.8
E	1.04	no	8.7
F	1.03	no	6.9
G	1.04	yes	6.8
XA	x	yes	7.3
XE	x	maybe	8.3

Table 2 summarizes the results of our calculations. We have chosen to focus on three diagnostic properties: the thickness of the HII region at the equator (expressed as a ratio of its inner and outer radii), the presence or absence of a density enhancement that (if actually azimuthally symmetric) could form an outer ring, and the expansion velocity of the inner ring.

4. Discussion

For the most part the interacting winds scenario seems to be on the right track for explaining the SN 1987A nebula. The expansion velocity of the inner ring is a bit low in these simulations, but it is close enough that it is reasonable to expect that some combination of parameters could be found to produce an acceptable match to the observed value.

The HII region is the most encouraging development in the simulations. Although the HII region is somewhat thin in the equatorial plane, the overall thickness seems to indicate that this problem could be fixed by judicious choice of wind parameters. Since the equatorial thickness of the HII region seems to go down with increasing β, further calculations will concentrate on calculations with smaller β.

Although we do see mid-latitude clumps in several of our simulations, we are skeptical that this means a mechanism has been found for producing the outer rings. We have seen that it is possible for these clumps to form even in the nonphotoionizing case, as the neutral shell breaks up due to Rayleigh-Taylor instabilities. Consequently, it seems likely that the clumps would not form axisymmetric rings in three dimensions. However, the edge of the nebular shell created by the ionization front could have an axisymmetric structure because its position is related to the density gradient in the RSG wind. Whether a dense ring could form there depends on the detailed cooling properties of the gas, which are only approximately accounted for in our models.

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